

Dijet and photon-jet correlations in proton-proton collisions at RHIC

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Abstract. We discuss correlations in azimuthal angle as well as correlations in two-dimensional space of transverse momenta of two jets as well as photon and jet. Some k_t -factorization subprocesses are included for the first time in the literature. Different unintegrated gluon/parton distributions are used in the k_t -factorization approach. The results depend on UGDF/UPDF used. The collinear NLO $2 \rightarrow 3$ contributions dominate over k_t -factorization cross section at small relative azimuthal angles as well as for asymmetric transverse momentum configurations.

1 Introduction

The subject of jet correlations is interesting in the context of recent detailed studies of hadron-hadron correlations in nucleus-nucleus [1] and proton-proton [2] collisions. Effects of geometrical jet structure were discussed recently in Ref.[3]. No QCD calculation of parton radiation was performed up to now in this context. Before going into hadron-hadron correlations it seems indispensable to better understand correlations between jets induced by the QCD radiation. Here we discuss the case of elementary hadronic collisions. Our analysis is a first step towards the nuclear case.

In leading-order collinear-factorization approach jets are produced back-to-back. These leading-order jets are therefore not included into correlation function, although they contribute a big ($\sim \frac{1}{2}$) fraction to the inclusive cross section. The truly internal momentum distribution of partons in hadrons due to Fermi motion (usually neglected in the literature) and/or any soft emission would lead to a decorrelation from the simple kinematical configuration.

In the fixed-order collinear approach only next-to-leading order terms lead to nonvanishing cross sections at $\phi \neq \pi$ and/or $p_{1,t} \neq p_{2,t}$ (moduli of transverse momenta of outgoing partons). In the k_t -factorization approach, where transverse momenta of gluons entering the hard process are included explicitly, the decorrelations come naturally in a relatively easy to calculate way. In Fig.1 we show diagrams included in our calculations which illustrate the physics situation. The soft emissions, not explicit in our calculation, are hidden in model unintegrated parton (gluon) distribution functions (UPDF,UGDF). In our calculation UGDFs or UPDFs are assumed to be given and are taken from the literature.

The k_t -factorization was originally proposed for heavy quark production [4]. In recent years it was used to describe several high-energy processes, such as total cross section in virtual photon - proton scattering [5], heavy quark inclusive production [6,7], heavy quark – heavy antiquark correlations [8,9], inclusive photon production [10,11], inclusive pion production [12,13], Higgs boson [14] or gauge boson [15] production and dijet correlations in photoproduction [16] and hadroproduction [17].

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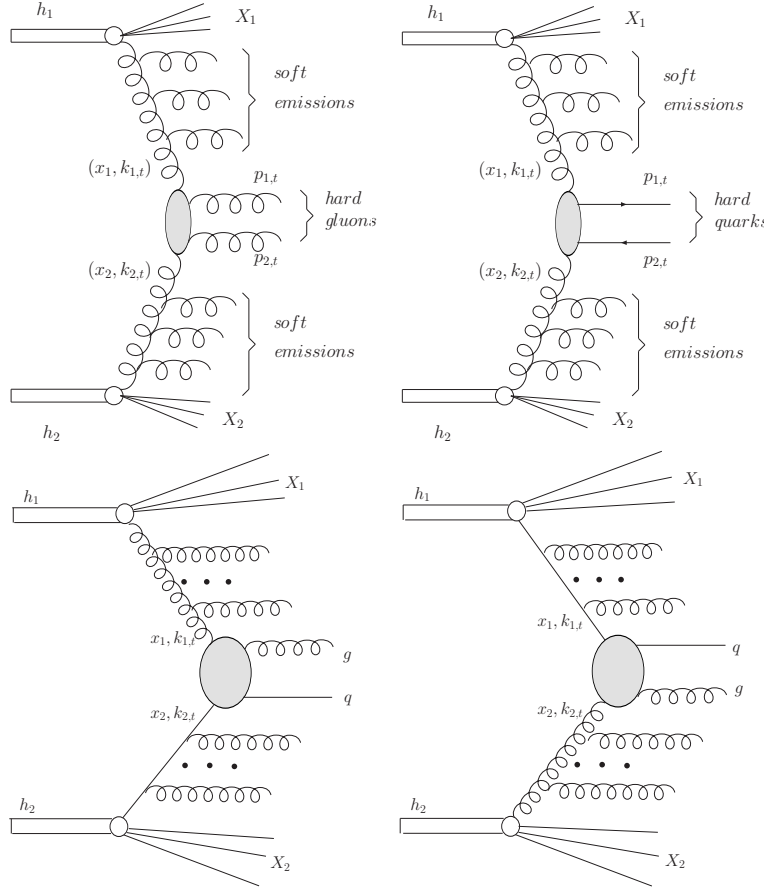


Fig. 1. Diagrams for k_t -factorization approach to dijet production.

Up to now no theoretical calculation for photon-jet were presented in the literature, even for elementary collisions. In leading-order collinear-factorization approach the photon and the associated jet are produced back-to-back. If transverse momenta of partons entering the hard process are included, the transverse momenta of the photon and the jet are no longer balanced and finite (non-zero) correlations in a broad range of relative azimuthal angle and/or in lengths of transverse momenta of the photon and the jet are obtained. The finite correlations can be also obtained in higher-order collinear-factorization approach [18].

Here we discuss the region of relatively semi-hard jets/photons, i.e. the region related to the recently measured hadron-hadron correlations at RHIC and photon-hadron correlations being analysed [19]. Here the resummation effects may be expected to be important. The resummation physics is addressed in our case through the k_t -factorization approach.

This presentation is based on recent publications of the authors [20,21]. Here we discuss only the main idea and present some representative results. More details can be found in Refs. [20,21].

2 Formalism

It is known that at high energies, at midrapidities and not too large transverse momenta of the jet (or photon) production is dominated by (sub)processes initiated by gluons. In this paper we concentrate on such processes. In this presentation we discuss mainly k_t -factorization approach. Some aspects of the standard collinear approach are discussed in Refs.[20,21].

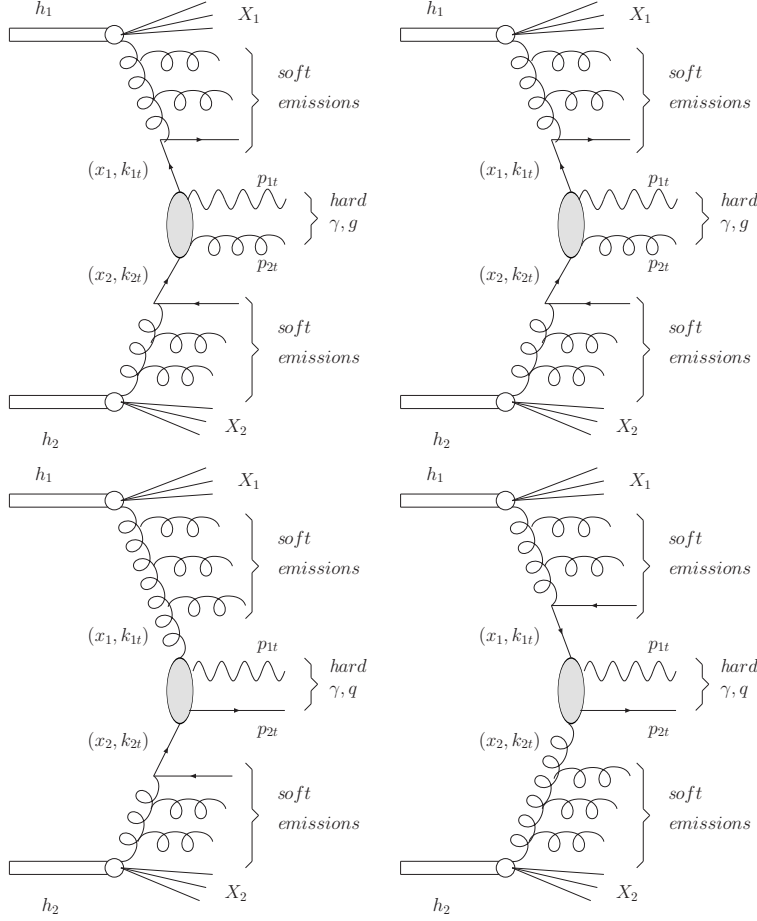


Fig. 2. Diagrams for k_t -factorization approach to photon-jet correlations.

In the k_t -factorization approach the cross section for the production of a pair of partons or photon and parton (k, l) can be written as

$$\frac{d\sigma(h_1 h_2 \rightarrow jet(\gamma) jet)}{d^2 p_{1,t} d^2 p_{2,t}} = \sum_{i,j,k,l} \int dy_1 dy_2 \frac{d^2 k_{1,t}}{\pi} \frac{d^2 k_{2,t}}{\pi} \frac{1}{16\pi^2 (x_1 x_2 s)^2} |\mathcal{M}(ij \rightarrow kl)|^2 \times \delta^2(\vec{k}_{1,t} + \vec{k}_{2,t} - \vec{p}_{1,t} - \vec{p}_{2,t}) \mathcal{F}_i(x_1, k_{1,t}^2) \mathcal{F}_j(x_2, k_{2,t}^2), \quad (1)$$

where

$$x_1 = \frac{m_{1,t}}{\sqrt{s}} e^{+y_1} + \frac{m_{2,t}}{\sqrt{s}} e^{+y_2}, \quad (2)$$

$$x_2 = \frac{m_{1,t}}{\sqrt{s}} e^{-y_1} + \frac{m_{2,t}}{\sqrt{s}} e^{-y_2}, \quad (3)$$

and $m_{1,t}$ and $m_{2,t}$ are so-called transverse masses defined as $m_{i,t} = \sqrt{p_{i,t}^2 + m^2}$, where m is the mass of a parton. In the case of photon-jet correlations there is no sum over k ($k = \gamma$). In the following we shall assume that all partons are massless. The objects denoted by $\mathcal{F}_i(x_1, k_{1,t}^2)$ and $\mathcal{F}_j(x_2, k_{2,t}^2)$ in the equation above are the unintegrated parton distributions in hadron h_1 and h_2 , respectively. They are functions of longitudinal momentum fraction and transverse momentum of the incoming (virtual) parton.

In Fig.1 we show the diagrams included for dijet correlations in Ref. [20].

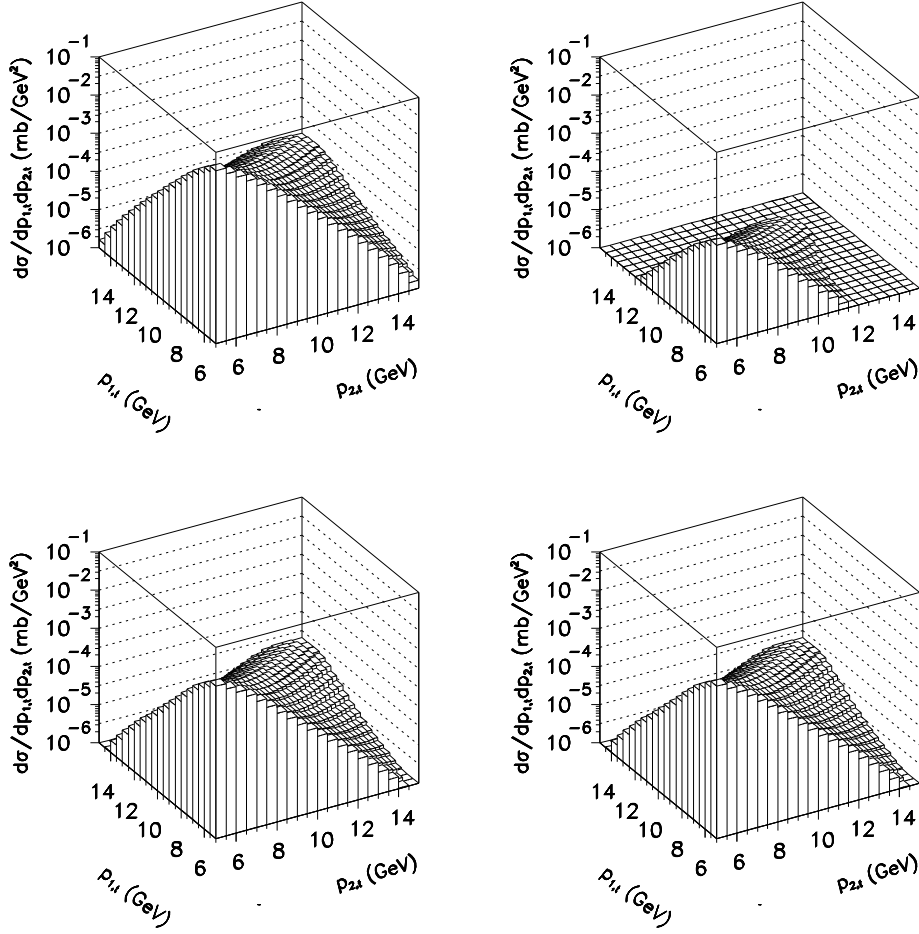


Fig. 3. Two-dimensional distributions in $p_{1,t}$ and $p_{2,t}$ for different subprocesses $gg \rightarrow gg$ (upper left) $gg \rightarrow q\bar{q}$ (upper right), $qq \rightarrow gg$ (lower left) and $qq \rightarrow q\bar{q}$ (lower right). In this calculation $\sqrt{s} = 200$ GeV and Kwieciński UPDFs with exponential nonperturbative form factor ($b_0 = 1 \text{ GeV}^{-1}$) and $\mu^2 = 100 \text{ GeV}^2$ were used. Here integration over full range of parton rapidities was made.

In Fig.2 we show similar diagrams included for photon-jet correlations in Ref. [21].

The formula (1) allows to study different types of correlations. Here we shall limit to a few examples. The details concerning unintegrated gluon (parton) distributions can be found in original publications (see [20,21] and references therein).

3 Results

3.1 Dijet correlations

In Fig.3 we show two-dimensional maps of the cross section in $(p_{1,t}, p_{2,t})$ for processes shown in Fig.1. Only very few approaches in the literature include both gluons and quarks and antiquarks. In the calculation above we have used Kwieciński UPDFs with exponential nonperturbative

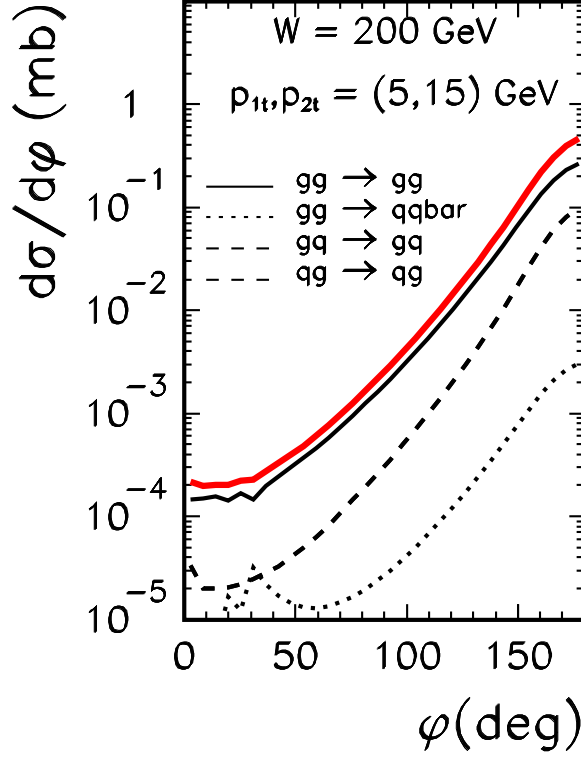


Fig. 4. The angular correlations for all four components: $gg \rightarrow gg$ (solid), $gg \rightarrow q\bar{q}$ (dashed) and $qq \rightarrow qq = gg \rightarrow qq$ (dash-dotted). The calculation is performed with the Kwieciński UPDFs and $b_0 = 1 \text{ GeV}^{-1}$. The integration is made for jets from the transverse momentum interval: $5 \text{ GeV} < p_{1,t}, p_{2,t} < 15 \text{ GeV}$ and from the rapidity interval: $-4 < y_1, y_2 < 4$.

form factor ¹ ($b_0 = 1 \text{ GeV}^{-1}$), and the factorization scale $\mu^2 = (p_{t,min} + p_{t,max})^2/4 = 100 \text{ GeV}^2$.

For completeness in Fig.4 we show azimuthal angle dependence of the cross section for all four components. There is no sizable difference in the shape of azimuthal distribution for different components.

The Kwieciński approach allows to separate the unknown perturbative effects incorporated via nonperturbative form factors and the genuine effects of QCD evolution. The Kwieciński distributions have two external parameters:

- the parameter b_0 responsible for nonperturbative effects, such as primordial distribution of partons in the nucleon,
- the evolution scale μ^2 responsible for the soft resummation effects.

While the latter can be identified physically with characteristic kinematical quantities in the process $\mu^2 \sim p_{1,t}^2, p_{2,t}^2$, the first one is of nonperturbative origin and cannot be calculated from first principles. The shapes of distributions depends, however, strongly on the value of the

¹ $F(b) = \exp(-b^2/4b_0^2)$ multiplies UPDFs in the impact parameter space and is responsible for non-perturbative effects included in addition to perturbative effects embedded in the Kwieciński evolution equations (for more details see e.g. [13]).

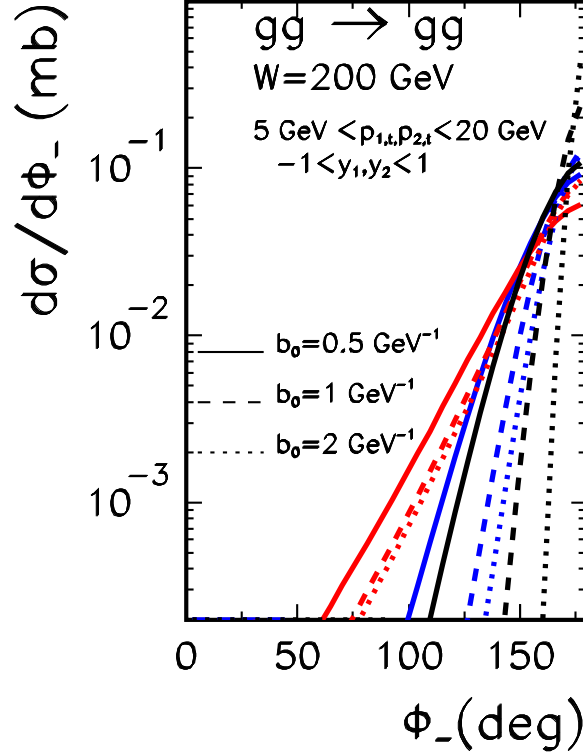


Fig. 5. The azimuthal correlations for the $gg \rightarrow gg$ component obtained with the Kwieciński UGDFs for different values of the nonperturbative parameter b_0 and for different evolution scales $\mu^2 = 10$ (grey, blue online), 100 (black, red online) GeV^2 . The initial distributions (without evolution) are shown for reference by black lines.

parameter b_0 . This is demonstrated in Fig.5 for the $gg \rightarrow gg$ subprocess. The smaller b_0 the bigger decorrelation in azimuthal angle can be observed. In Fig.5 we show also the role of the evolution scale in the Kwieciński distributions. The QCD evolution embedded in the Kwieciński evolution equations populate larger transverse momenta of partons entering the hard process. This significantly increases the initial (nonperturbative) decorrelation in azimuth. For transverse momenta of the order of ~ 10 GeV the effect of evolution is of the same order of magnitude as the effect characteristic for the nonperturbative physics. For larger scales of the order of $\mu^2 \sim 100$ GeV^2 , more adequate for jet production, the initial condition is of minor importance and the effect of decorrelation is dominated by the evolution. Asymptotically (infinite scales) there is no dependence on the initial condition provided reasonable initial conditions are taken.

In Fig.6 we show azimuthal-angle correlations for the $gg \rightarrow gg$ component (dominant at midrapidities) for different UGDFs from the literature. Rather different results are obtained for different UGDFs. In principle, experimental results could select the “best” UGDF. We do not need to mention that such measurements are not easy at RHIC and hadron correlations are studied instead of jet correlations.

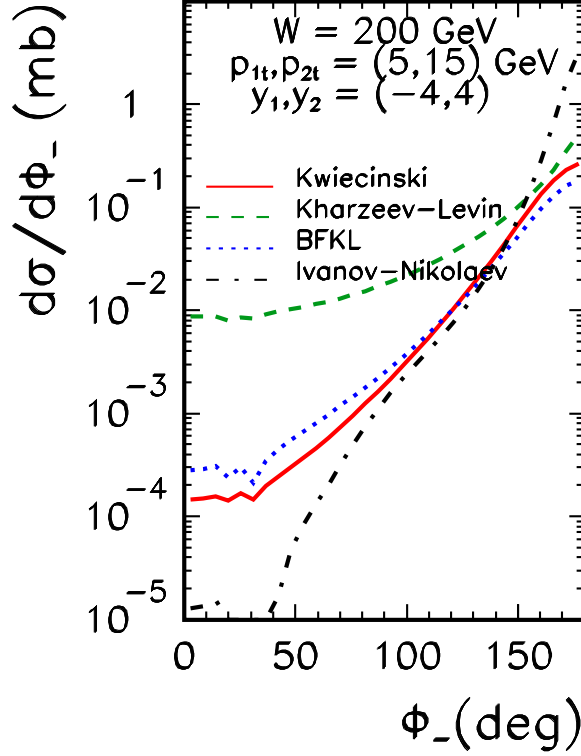


Fig. 6. Azimuthal angle correlations between two jets for different unintegrated gluon distributions.

3.2 Photon-jet correlations

Let us start from presenting our results on the $(p_{1,t}, p_{2,t})$ plane. In Fig.7 we show the maps for different UPDFs used in the k_t -factorization approach as well as for NLO collinear-factorization approach for $p_{1,t}, p_{2,t} \in (5, 20)$ GeV and at the Tevatron energy $\sqrt{s} = 1960$ GeV. In the case of the Kwieciński distribution we have taken $b_0 = 1$ GeV $^{-1}$ for the exponential nonperturbative form factor and the scale parameter $\mu^2 = 100$ GeV 2 . Rather similar distributions are obtained for different UPDFs. The distribution obtained in the NLO approach differs qualitatively from those obtained in the k_t -factorization approach. First of all, one can see a sharp ridge along the diagonal $p_{1,t} = p_{2,t}$. This ridge corresponds to a soft singularity when the unobserved parton has very small transverse momentum $p_{3,t}$. At the same time this corresponds to the azimuthal angle between the photon and the jet being $\phi_- = \pi$. Obviously this is a region which cannot be reliably calculated in collinear pQCD. There are different practical possibilities to exclude this region from the calculations [21].

As discussed in Ref.[22] the Kwieciński distributions are very useful to treat both the nonperturbative (intrinsic nonperturbative transverse momenta) and the perturbative (QCD broadening due to parton emission) effects on the same footing. In Fig.8 we show the effect of the scale evolution of the Kwieciński UPDFs on the azimuthal angle correlations between the photon and the associated jet. We show results for different initial conditions ($b_0 = 0.5, 1.0, 2.0$ GeV $^{-1}$). At the initial scale (fixed here as in the original GRV [23] to be $\mu^2 = 0.25$ GeV 2) there is a sizable difference of the results for different b_0 . The difference becomes less and less pronounced when the scale increases. At $\mu^2 = 100$ GeV 2 the differences practically disappear. This is due to the

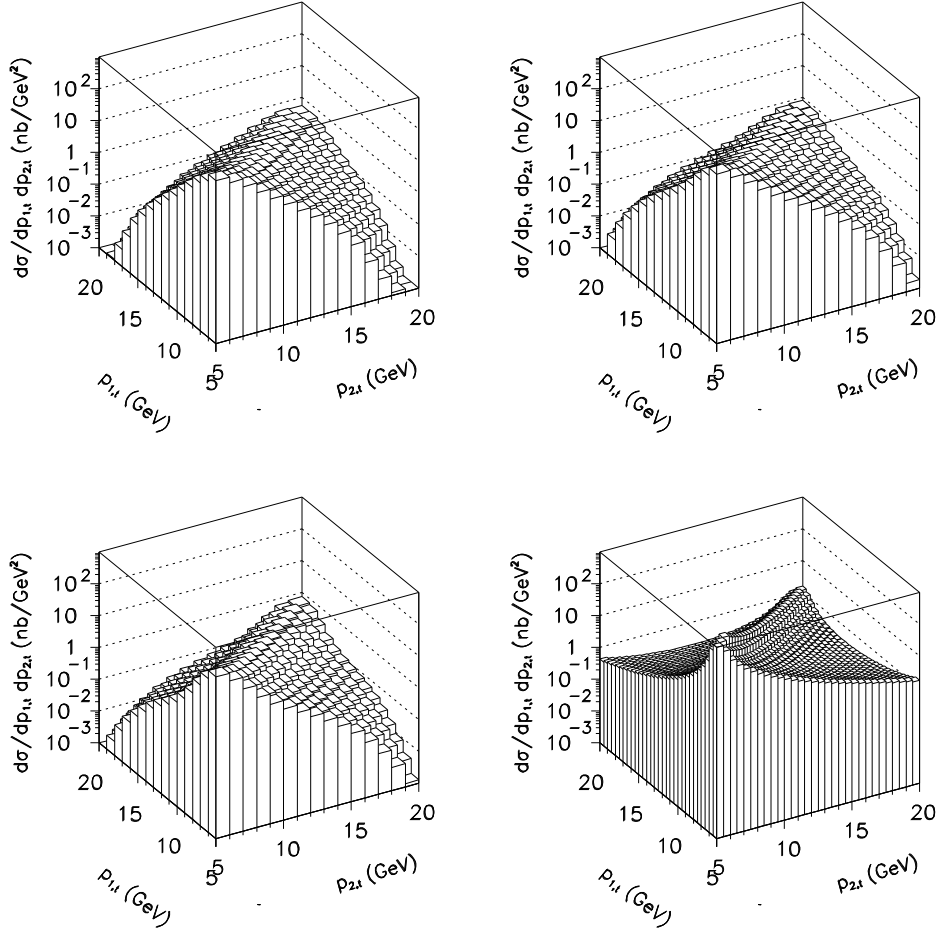


Fig. 7. Transverse momentum distributions $d\sigma/dp_{1,t}dp_{2,t}$ at $\sqrt{s} = 1960$ GeV and for different UPDFs in the k_t -factorization approach for Kwieciński ($b_0 = 1 \text{ GeV}^{-1}$, $\mu^2 = 100 \text{ GeV}^2$) (upper left), BFKL (upper right), KL (lower left) and NLO $2 \rightarrow 3$ collinear-factorization approach (lower right). The integration over rapidities from the interval $-5 < y_1, y_2 < 5$ is performed.

fact that the QCD-evolution broadening of the initial parton transverse momentum distribution is much bigger than the typical initial nonperturbative transverse momentum scale.

In Fig.9 we show azimuthal angular correlations for RHIC. In this case integration is made over transverse momenta $p_{1,t}, p_{2,t} \in (5, 20)$ GeV and rapidities $y_1, y_2 \in (-5, 5)$. The standard NLO collinear cross section grows somewhat faster with energy than the k_t -result with unintegrated Kwieciński distribution. This is partially due to approximation made in calculation of the off-shell matrix elements.

Let us consider now some aspect of the standard NLO approach. Here 3 jets with transverse momenta $p_{1,t}, p_{2,t}$ and $p_{3,t}$ are produced². In Fig.10 we show angular azimuthal correlations for different interrelations between transverse momenta of outgoing photon and partons: (a) with no constraints on $p_{3,t}$, (b) the case where $p_{2,t} > p_{3,t}$ condition (called leading jet condition in the following) is imposed, (c) $p_{2,t} > p_{3,t}$ and an additional condition $p_{1,t} > p_{3,t}$. The results depend significantly on the scenario chosen as can be seen from the figure. The general pattern is very much the same for different energies. The figure demonstrates that only higher-orders

² Jet 1 (with $p_{1,t}$) and jet 2 (with $p_{2,t}$) are those which correlations are studied.

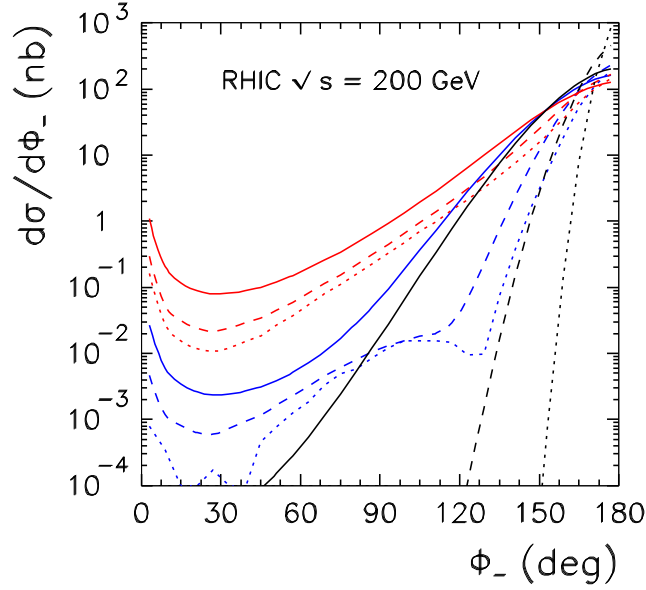


Fig. 8. (Color online) Azimuthal angle correlation functions at RHIC energies for different scales and different values of b_0 of the Kwieciński distributions. The solid line is for $b_0 = 0.5 \text{ GeV}^{-1}$, the dashed line is for $b_0 = 1 \text{ GeV}^{-1}$ and the dotted line is for $b_0 = 2 \text{ GeV}^{-1}$. Three different values of the scale parameters are shown: $\mu^2 = 0.25, 10, 100 \text{ GeV}^2$ (the bigger the scale the bigger the decorrelation effect, different colors on line). In this calculation $p_{1,t}, p_{2,t} \in (5, 20) \text{ GeV}$ and $y_1, y_2 \in (-5, 5)$.

contribute to the region of small relative angles. The same is true for dijet correlations discussed in Ref.[20]. We wish to notice that there are no such limitations in the k_t -factorization approach which implicitly include the higher orders.

4 Conclusions

Motivated by the recent experimental results of hadron-hadron correlations at RHIC we have discussed jet-jet and photon-jet correlations.

In comparison to recent works on dijet production in the framework of k_t -factorization approach, we have included two new mechanisms based on $gq \rightarrow gq$ and $qg \rightarrow qg$ hard subprocesses. This was done using the Kwieciński unintegrated parton distributions. We find that the new terms give significant contribution at RHIC energies. In general, the results of the k_t -factorization approach depend on UGDFs/UPDFs used, i.e. on approximation and assumptions made in their derivation.

An interesting observation has been made for azimuthal angle correlations. At relatively small transverse momenta ($p_t \sim 5\text{--}10 \text{ GeV}$) the $2 \rightarrow 2$ subprocesses, not contributing to the correlation function in the collinear approach, dominate over $2 \rightarrow 3$ components. The latter dominate only at larger transverse momenta, i.e. in the traditional jet region.

The results obtained in the standard NLO approach depend significantly whether we consider correlations of any jets or correlations of only leading jets. In the NLO approach one obtains $\frac{d\sigma}{d\phi_-} = 0$ if $\phi_- < \frac{2}{3}\pi$ for leading jets as a result of a kinematical constraint. Similarly $\frac{d\sigma}{dp_{1,t}dp_{2,t}} = 0$ if $p_{1,t} > 2p_{2,t}$ or $p_{2,t} > 2p_{1,t}$. In this presentation we have discussed explicitly only a similar case of photon-jet correlations.

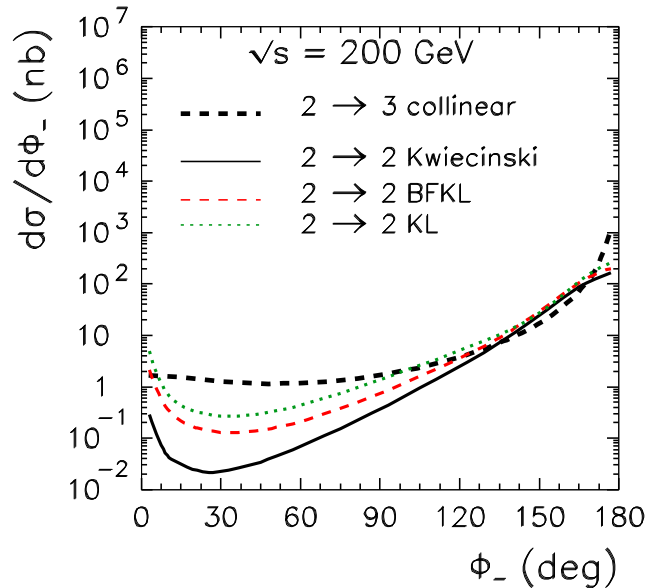


Fig. 9. Photon-jet angular azimuthal correlations $d\sigma/d\phi_-$ for proton-(anti)proton collision at $\sqrt{s} = 200$ GeV for different UPDFs in the k_t -factorization approach for the Kwieciński (solid), BFKL (dashed), KL (dotted) UPDFs/UGDFs and for the NLO collinear-factorization approach (thick dashed). Here $y_1, y_2 \in (-5, 5)$.

There is no such a constraint in the k_t -factorization approach which gives a nonvanishing cross section at small relative azimuthal angles between leading jets and transverse-momentum asymmetric configurations. We conclude that in these regions the k_t -factorization approach is a good and efficient tool for the description of leading-jet correlations. Rather different results are obtained with different UGDFs which opens a possibility to verify them experimentally.

On the contrary, in the case of correlations of any unrestricted jets (all possible dijet combinations) the NLO cross section exceeds the cross section obtained in the k_t -factorization approach with different UGDFs. This is therefore a domain of the standard fixed-order pQCD. We recommend such an analysis as an alternative to study leading-jet correlations.

Consequences for particle-particle correlations, measured recently at RHIC, require a separate dedicated analysis.

We have discussed also photon-jet correlation observables. Up to now such correlations have not been studied experimentally. As for the dijet case we have concentrated on the region of small transverse momenta (semi-hard region) where the k_t -factorization approach seems to be the most efficient and theoretically justified tool. We have calculated correlation observables for different unintegrated parton distributions from the literature. Our previous analysis of inclusive spectra of direct photons suggests that the Kwieciński distributions give the best description at low and intermediate energies. We have discussed the role of the evolution scale of the Kwieciński UPDFs on the azimuthal correlations. In general, the bigger the scale the bigger decorrelation in azimuth is observed. When the scale $\mu^2 \sim p_t^2(\text{photon}) \sim p_t^2(\text{associated jet})$ (for the kinematics chosen $\mu^2 \sim 100 \text{ GeV}^2$) is assumed, much bigger decorrelations can be observed than from the standard Gaussian smearing prescription often used in phenomenological studies.

The correlation function depends strongly on whether it is the correlation of the photon and any jet or the correlation of the photon and the leading-jet which is considered. In the last case there are regions in azimuth and/or in the two-dimensional $(p_{1,t}, p_{2,t})$ space which cannot be

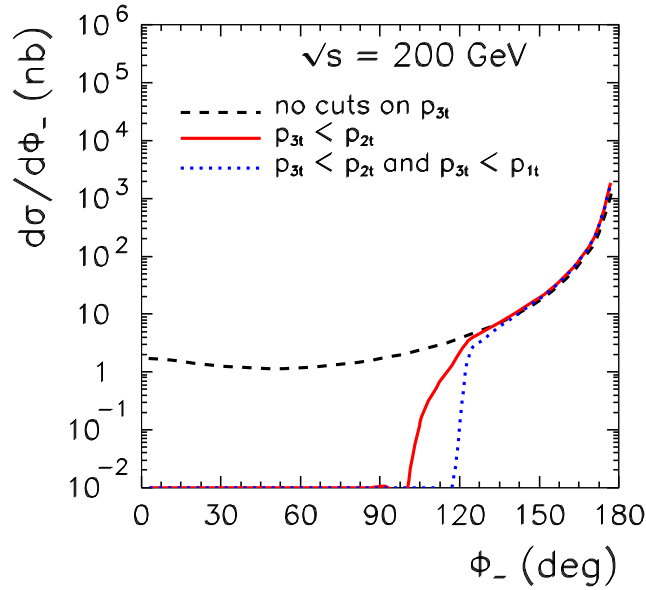


Fig. 10. Angular azimuthal correlations for different cuts on the transverse momentum of third (un-observed) parton in the NLO collinear-factorization approach without any extra constraints (dashed), $p_{3,t} < p_{2,t}$ (solid), $p_{3,t} < p_{2,t}$ and $p_{3,t} < p_{1,t}$ in addition (dotted). Here $\sqrt{s} = 200$ GeV and $y_1, y_2 \in (-5, 5)$.

populated in the standard next-to-leading order approach. In the latter case the k_t -factorization seems to be a useful and efficient tool.

At RHIC one can measure jet-hadron correlations only for not too high transverse momenta of the trigger photon and of the associated hadron. This is precisely the semihard region discussed here. In this case the theoretical calculations would require inclusion of the fragmentation process. This can be done easily assuming independent parton fragmentation method.

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